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ABSTRACT

Fire growth on the surface of a composite in a vertical corner configuration was chosen to represent a moderately severe test for materials to be used in infrastructure applications. An approximate model for predicting the extent of this fire growth is summarized here. It is based on a bench-scale characterization of the material properties and full-scale measurements of the heat flux pattern imposed by a varied ignition source. The model predictions for a vinyl ester/glass composite are compared with full-scale fire growth and heat release rate data for three sizes of igniter flame, yielding reasonable agreement.

KEY WORDS: Composite Structures, Flammability, Fire Growth, Infrastructure

1. INTRODUCTION

This paper is part of a study of the flammability of composite materials such as are found in infrastructure applications. The composites of interest are fiber-reinforced polymer resins, including such combinations as polyester/glass, vinyl ester/glass, phenolic/glass and epoxy/carbon fiber. (Cost limitations preclude more exotic resin and/or fiber systems.) This is a relatively new and still developing area but applications of current interest include the construction and repair of highway and pedestrian bridges as well as retrofit reinforcement of support columns for elevated highways, parking structures and other buildings in earthquake-prone areas. There is also interest in applying such materials to occupied structures. Many of these applications would leave the composite material exposed on the exterior surface of the structure. These surfaces may be horizontal or vertical, flat, convex or concave, depending on the particular design.

The fire threats to such composites are not well-defined (in terms of likely imposed heat flux and area affected on a structure or in terms of probability of occurrence) but include, for exterior

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structures like bridges, such items as fuel spills resulting from a vehicular crash, also brush or forest fires and arson/vandalism; in occupied structures, the list of threats shifts to include all of the varied contingencies which lead to building fires. The necessity of addressing these fire threats depends on the application. Applications to occupied structures would have to conform to existing building codes. In practice, this usually translates into a need for a specified level of performance in ASTM E-84 (tunnel test for surface flame spread) and ASTM E-119 (fire endurance of structural elements). The pertinence of these tests to the real fire performance of composite-reinforced structures has not been established (and is in need of research), but the existence of these requirements is probably a major reason why there has been very little attempt to market composites in such application areas, as yet. For exterior structures such as bridges or for highway column and deck reinforcement, the desirability of addressing fire vulnerability depends on the cost of the consequences of a fire; there are no existing fire resistance requirements because these applications are without precedent. If the only consequence is that the structure will have to be repaired or replaced following a fire, then it is an economic decision, balancing the cost of fire resistance versus the cost and frequency of repair/replacement over the expected lifetime of the structure. Unfortunately there are no data or other guidelines available at present that could allow one to predict the consequences of a given fire scenario in terms of likely extent of damage to the structure. The present work is a first attempt in this direction.

The consequences of any fire exposure of a composite structure fall into two categories. First is the threat of localized weakening of the composite in the area where the heat source directly impinges on it. Polymer resins soften and/or degrade chemically when heated by an amount that varies with the resin; this nullifies their ability to transfer loads among the fibers, leading to a local loss of strength. The consequences of this depend on the criticality (to the entire structure) of the composite elements being heated. The second category of fire exposure consequences is potentially more serious: the polymer resin may ignite and become part of the fire. In the worst case the localized fire exposure could then lead to full fire involvement of the entire composite portion of the structure. There are gradations of hazard here which depend on the extent of fire growth on the composite material, though clearly any fire growth puts the structure at greater risk because it enlarges the portion which is thermally weakened. Extent of **fire** growth, in turn, depends on the size of the initiating fire, the nature of the composite and the configuration in which it exists. It is this variable hazard problem upon which the current work is focused. We are seeking some means to estimate the extent of fire growth on such fire-exposed composite structures. The related problem, loss of strength in fire exposed areas, is also of interest but is being addressed in separate work.

The prior work on surface fire growth over conventional wall materials in a vertical corner configuration (e.g., 1, 2, 3) is a natural point of departure for the present problem, despite the fact that this specific geometry is only one of many which may occur in a composite structure. It is representative of one of the more seriously threatened configurations. Fire growth via upward flame spread is the worst case for these structures, just as it is in a corner of a building compartment. Upward spread tends to be more severe because of the enhanced heat transfer between the upswept buoyant fire plume and the unignited fuel surface. Fire spread on the underside of downward facing, horizontal components, e.g., the underside of a bridge deck, is at least qualitatively similar. Both corner and composite structure application situations include an

element of lateral flame spread, as well. The 90° corner provides an added element of severity since radiative feedback between the two flaming surfaces mutually strengthens the burning process of each while partial blockage of air entrainment slows the dilution of the fire plume, allowing it to heat the unignited fuel over a longer distance (and thus a longer time, if the fire is spreading). This particular corner angle is natural for room fires, but not necessarily so for infrastructural composites. It is one possible choice abetted here by the fact that needed data on fire plume behavior are available for this case. It is probably more severe than structural configurations with more oblique angles and thus is conservative in somewhat overestimating likely fire growth in designs with more open angles on vertical structural elements.

It should be noted that prior work on corner fire growth was motivated by the desire to predict the outcome of standard fire tests on compartment wall lining materials. The outcome of interest was the time of compartment flashover (full fire involvement). Here we focus on an open corner (not contained within a compartment) and are concerned with the rate and extent of fire growth on the two vertical surfaces. The ultimate goal is to be able to predict this, as a function of material and ignition source properties, using only data obtained from bench scale tests. Such a model could be used to estimate how much of a composite structure is at risk as a result of various fire exposures. The model described here utilizes bench-scale data to characterize the composite material but it still requires some full-scale input data on the heat flux distribution imposed by the ignition source. The model and the solution code reported here are described in more detail in Reference 4.

2. MODEL DESCRIPTION

The corner fire growth problem is quite complex because it is three-dimensional, as well as being time dependent and involving coupled gas and solid phases. Figure 1 illustrates the various elements of the problem schematically; note that the fire spreads most rapidly up the vertex region of the corner. To date, there have been no attempts to attack this problem in its full complexity. Instead, the gas phase is characterized semi-empirically by means of correlations for flame height and heat transfer from the ignition source to the wall surface. Heat transfer from the upward moving flames on the burning solid is also treated similarly. The burning rate (and thus the heat release rate) of the ignited solid surface is derived either from bench-scale measurements as a function of incident heat flux or from a simplified mass burning rate model. However, as will be seen below in the current model description, there are significant unknowns regarding the most accurate way to describe these various elements.

The model developed here is a significant extension of the corner fire growth model of Quintiere [3]. That model is based on two simple, semi-empirical expressions, one for the rate of upward flame spread and the other for the rate of lateral flame spread that results from the impingement of an ignition source at the base of the corner configuration. (The sloped burning front in Figure 1 can be thought of as resulting from a combination of upward and lateral spread. Here that front is taken to be line where the ignition temperature is reached. It is also referred to as the pyrolysis front.) That model uses the simplest expression for the profile of heat transfer from the flame to the wall above the ignition front (pyrolysis front), i.e., that the flux is constant from the ignition front to the end of the flame. In the referenced version it also assumed that the heat release rate

from ignited wall material was constant with respect to time.

Referring to Figure 1, one sees that the scenario of interest includes a variable-sized ignition source at the base of the corner formed by the vertical slabs of material. In the experiments which the model will be compared with below, the ignition source was a sand-filled, square burner fueled by propane. Both the lateral extent of the ignition source and its heat release rate may vary but its flames always originate at the base of the corner. This represents an idealization of the range of real-world ignition sources to which a composite structure may be exposed. Symmetry about the corner vertex is assumed so that the model described below follows fire growth on one surface only.

Following Quintiere [3], we adopt the following simple rate expression for upward flame spread rate on a vertical fuel surface.

$$\frac{d y_p}{dt} = \frac{(y_f - y_p)}{t_{ign}} \quad (1)$$

Here y_p is the height of the pyrolysis (flame) front above the top of the burner igniter. This is the maximum height of burning material on the wall surfaces, i.e., the pyrolysis front is also the burning front. The quantity y_f is the height of the flame (due to the combined effects of the burner and the burning material on the walls); it is computed from empirical correlations as described below. In general it extends beyond the pyrolysis front; if not the upward growth rate is zero. The quantity t_{ign} is derived from the empirical ignition delay time (measured in **ASTM E-1354** Cone Calorimeter or **ASTM E-1321 LIFT** tests, for example) required to take the wall material from its "initial" temperature to its ignition temperature in response to the heat flux input it sees from the flames imposed by the igniter or burning wall material, plus radiative interchange between the walls. These laboratory-derived ignition data are typically for samples starting at room temperature. The ignition delay is assumed to behave, in response to pre-heating from the igniter flames, as one would infer for a simple thermally thick solid, i.e.

$$t_{ign} \propto (T_{ign} - T_s)^2$$

Where T_{ign} is the empirical ignition temperature of the material; here it is inferred from a heat balance on the sample surface at the measured minimum flux for ignition (again, typically in the Cone Calorimeter or LIFT apparatus). During the upward flame spread process, the quantity T_s refers to the pre-heated "initial" temperature of the wall surface just before it begins to come under the influence of the flames from the burning wall material. Here that pre-heating is taken to be a consequence of the heat flux distribution imposed by the burner which is causing wall ignition. Thus we are separating out the effects on the sample of the burner heat flux and the sample's own flame heat flux. The extent of local pre-heating by the burner flames is calculated

from a one-dimensional integral model described in Ref. 4. The local ignition delay time is then corrected for this pre-heat in accord with the thermally-thick expression above.

Note that this flame spread expression (Eq. 1) is rather intuitive in nature rather than strictly derivable. It literally says that the ignition front moves up a distance of one sample flame height in the time it takes to ignite this length of material being heated by the sample's own flame. It is true if the flux from the flame is uniform over the flame height and, indeed, that assumption is used throughout this model. However, Kulkarni [5] has shown that a better description of the flux from the flame is that it decreases exponentially above the ignition front, continuing to be finite up to about three times the flame height. Here the average of an exponential distribution (measured for the materials used here) over one flame height is used as the spatially constant flame flux; see [4] for further details.

The steady-state wall heat flux pattern imposed by the burner positioned at the base of the corner has been measured (with limited spatial resolution on inert wall materials) for a few burner size and burner power combinations [7, 8, 9, 10]. It is this imposed heat flux distribution which initiates the fire on the composite walls and heavily influences its early history of growth. Figure 2a, measured during the study reported in Ref. 7, is an example of the imposed flux distribution when propane was fed to a rather small burner yielding a tall, narrow flame. These results were obtained after the inert (calcium silicate) wall had reached a steady temperature under the influence of continuous contact with the burner flames.⁷ The flux values constitute cold wall heat fluxes pertinent to the early heat-up of the wall surfaces. For each burner size and power level of interest, the two dimensional pattern of isoflux lines is approximated in the model by a set of nested, isoflux rectangles; see Figure 2b for an example. The flux resolution level of the bands is taken as 20 kW/m^2 ; thus the smallest central rectangle represents the area on which there are fluxes of 80 kW/m^2 and above (zero area in Fig. 2b), the band outside of this having fluxes between 80 and 60 kW/m^2 , etc., down to zero incident flux. The area in each isoflux band is the same as that measured experimentally between the particular pair of isoflux contours. The actual flux level taken to apply to a given band is the mean of the isoflux line values which define it. For the area inside the 80 kW/m^2 isoflux line, an appropriate average is estimated from the available inert wall data.

The single upward flame spread front in the model moves upward through this approximated flux distribution in accord with a numerical solution of Eqn. (1), using a fourth -order Runge-Kutta routine. The extent of burner-imposed pre-heating of the wall at a given location in a flux band is determined by the time (from the start of the burner) at which the pyrolysis front arrives. The preheating by the burner flame flux pattern is assumed to be going on independently of that due to the more localized flux from the flames on the wall material.

⁷This pattern as measured for calcium silicate walls is what is used in the present model study. However, as discussed in Ref. 4, the pattern imposed by the burner on the vinyl ester/glass composite walls is somewhat more complex in that it has an initial transient growth period. The transience of the flux is included but the implied movement of the flux band boundaries is not,

FIRE SAFE MATERIALS—I

Each nested rectangle approximation of the flux pattern immediately suggests the way in which lateral flame spread is to be handled in this model. As the vertical front moves up and passes into each new isoflux band, it initiates a new lateral spread front in that band. All lateral flame spread fronts are taken to be described by the same type of expression:

$$\frac{dy_{Ln}}{dt} = V_{Ln} = \frac{\Phi}{(k\rho C)(T_{ign} - T_s)^2} \quad (2)$$

where y_{Ln} is the position, relative to the corner vertex as zero, of lateral flame spread front n (where $n = 1$ to **5**); Φ is the effective flame heat flux parameter, as measured in ASTM E-1321 (LIFT test); $(k\rho C)$ is the effective thermal inertia of the composite, inferred from radiative ignition data in the Cone Calorimeter or LIFT. The value of the ignition temperature, T_{ign} , is the same as in Eq. 1 above. This expression also responds to preheating by the burner heat flux in each particular flux band through the value of T_s , the temperature of the composite at the time when the lateral front reaches it. This time-varying pre-heat temperature is found from the same integral model as is used to compute pre-heating for the upward spread process. Each lateral spread equation is solved simultaneously at each time step with the upward spread equation using the Same RK-4 routine mentioned previously.

In the model, the lateral spread fronts arise as follows. First the highest flux band (closest to the burner) is taken to ignite uniformly at a time appropriate to its estimated average flux and this starts the spread process at this finite time. The vertical front thus begins its upward movement in flux band **2** at the same time as the first (and, at this time, only) lateral flame spread front also begins to move outward. The initial value of the vertical and lateral front position is equal to the height and width of flux band **1**, respectively. The vertical front is typically faster than this lateral front (at least initially). (Note that the vertical front grows in width as a result of the lateral front spread.) The vertical front thus passes into the next heat flux band (i.e., band **3**) before the lateral front has left flux band **2**. As the vertical front crosses the border between the two bands, a new lateral front is initiated with a starting position equal to the width of the vertical front at the moment of crossing. This process continues to generate more lateral pyrolysis fronts (up to five) as long as the conditions are conducive to flame spread. Figure 3 shows an example of a set of front positions within the nested set of flux bands for a particular ignition burner condition that is discussed further below. Eventually the vertical pyrolysis front may slow allowing some or all of the lateral fronts to reach the Same burner flux band as that in which it resides. Also note that the composite materials of interest here always have a finite minimum incident external flux required to sustain lateral flame spread; thus lateral spread never occurs beyond the outermost burner flux band and it may not reach that band.

Once ignited by the passage of a pyrolysis front (flame front), the wall material proceeds to bum, releasing heat which adds to the burner heat release and extends the flame upward on the walls. One relation between flame height and total heat release rate used here is the empirical result obtained by Kokkala [6] for average flame height from gas burner flames at the base of a 90° corner. In this correlation, flame height is proportional to burner flame heat release rate to the 0.9

power and it is inversely proportional to burner width to the 1.25 power. This correlation was obtained for a burner at the base of a corner formed by inert walls, thus the source of the flames was always at a fixed height (zero). Here we have both a burner and a growing wall fire in the corner. That is, part of the source of the flames is moving up the wall and this must cause the flame tip height to move up also. Hasemi, *et al* give a correlation for a 90° corner which confirms that flame height is higher when the wall is the source of the flames [9]. In the model the combined flames are treated empirically as follows. Hasemi's correlation is used to infer an equivalent wall fire heat release rate which gives the same flame height as does Kokkala's base burner correlation. This equivalent heat release rate for the burner is then added to the heat release rate from the wall and the resulting flame height is inferred from Hasemi's correlation. Since the wall flame is non-uniform in its heat release rate (due to non-uniform heat flux), the model calculates the heat release-weighted centroid of the wall flame area and uses it in the Hasemi wall flame height correlation.

The heat release rate behind the upward and lateral moving pyrolysis (flame) fronts depends on the spatially varying incident heat flux. The model uses an empirical relationship between the measured heat flux to the surface and the heat release rate. This relation was measured here in the Cone Calorimeter for the particular vinyl ester/glass composite for which full scale fire spread data were also available; it requires embedding a heat flux gage into the sample. See Ref. 4 for details. The model sums up the spatially varying contributions to total heat release rate at each time step in order to track the flame height which is driving the upward spread process. Data on the burn out time of the composite (here 1.27 cm thick) as a function of external flux are also obtained from the Cone Calorimeter. For the cases examined here, burnout occurred only after full height flame spread and thus did not influence the results.

The model predicts the upward and lateral movement of the various flame fronts as a function of time subsequent to the appearance, at time zero, of the approximated heat flux distribution from a given size of igniter flame. (That igniter flame exposure continues throughout the time intervals reported here.) The model also calculates the total heat release rate from the growing fire. This is of more importance to a fire in an enclosure but it is also of interest here as a check on the model prediction since such data are available for the vinyl ester composite used below to test the model.

3. RESULTS AND DISCUSSION

Results from a previously reported study [7] are used here to check the model predictions. That study involved two sizes of square, sand-filled propane burners placed against the base of two slabs of brominated vinyl ester/woven roving glass composite, 1.27 cm thick by 2.44 m high, forming a vertical, 90° corner. The two burners were run at three propane flow rates.

It should be noted that the experimental configuration did include a flat ceiling segment at the top of the corner, since that previous study was ultimately aimed at compartment fire growth. However, the set-up was in the open, not in a compartment. Thus the ceiling segment is believed to have affected only the fire growth near the top of the corner. Heat feedback from the ceiling segment may have accelerated heat release and thus fire growth in the top 10-20 cm of the corner.

for the smaller fires here. The effect may have been larger for the biggest fire, as described below.

Here the principal comparison between model and experiment is the position of the upward flame spread front as a function of time. The model also predicts lateral growth but it is typically much less in extent and thus less sensitive as a diagnostic. In no case did experiment or model yield spread appreciably wider than the propane burner.

Figures 3 and 4 show the predicted fire front growth behavior as a function of time for the case of a 38 cm wide burner operated at a propane flow rate that provides a 60 kW igniter flame. For reference, such a burner heat release rate corresponds to a rather small trash fire. However, the high temperature of the propane flame is likely to impose a higher peak heat flux on the composite than would, say, burning paper-based trash.

In Figure 3 one sees the predicted pyrolysis front positions for this case at two times, 500 seconds apart. It is clear that upward spread is much faster than lateral spread. This leads to an upward moving front which does not change much in width as it progresses. Note also that the minimum required incident heat flux for lateral spread on this particular flame-retarded vinyl ester composite was measured in the LIFT (ASTM 1321) as 15 kW/m^2 . Here this means that the model allows no lateral spread in the igniter flux band that covers the range $0\text{--}20 \text{ kW/m}^2$. As a result, in the right hand portion of Fig. 3, the lowest three lateral spread fronts have all lined up where they stopped at the inner border of this flux band. For the same reason, the two higher fronts do not move at all after they are created by the upward moving flame front.

In Figure 4, the upward spreading flame front in the model prediction starts at a height of about 0.5 m because this was the height of the highest flux band imposed by the igniter flame. Thus the material from zero to 0.5 m all ignites at once after a time corresponding to the ignition delay for this vinyl ester composite at the roughly 80 kW/m^2 imposed heat flux from the burner. The subsequent upward spread is rapid at first while the spread front is still in the high flux bands imposed by the igniter flame but it slows substantially as the flux drops. Reference to Figure 3 shows that the igniter flux is approximated as zero above 1.56 m. In spite of this, the model predicts that the upward spread of the flame front continues to the top of the corner at 2.44 m, reaching there at about 900 seconds. The finite slope at this point implies that the upward spread would have continued further on a taller corner.

The experimental data from a pair of replicate tests are shown as black dots in Figure 4. In contrast to the model, the experimental data have a finite slope even near the bottom of the corner, reflecting the fact the imposed burner heat flux was decreasing smoothly with height, not in finite steps as the model assumes. The slope over the entire test duration was generally somewhat less than the model predicted. However, the model has successfully captured the essence of the upward spread behavior in a semi-quantitative manner. The prediction is conservative in that it over-predicts the extent of spread.

As is noted in Figure 4, the model predicts a peak heat release rate (burner plus composite) of 106 kW; the two experiments gave values of 112 kW and 116 kW, respectively. The peak occurs essentially at the end of the spread shown here, before the lowest, earliest-ignited regions begin to

turn out due to the finite thickness of the composite. This total heat release rate prediction is another quality check on the model which sums the varying contributions from all of the various burning area segments within the flux band system.

A real composite structure would possibly be taller (perhaps much taller) than the 2.44 m (8 ft) corner tested here. Thus one would be interested in how far upward the fire may ultimately grow. This is an issue that has not yet been addressed. Of equal interest is the rate of growth relative to the time of any suppression response, e.g., by a fire department. This is context dependent. The 2.4 m growth in 15-20 minutes seen in Fig. 4 would probably allow an adequate fire fighting response in an urban environment but it could imply that the fire would run its full course if the composite structure **was** a bridge in a rural area.

Figure 5a shows a comparison of a model prediction with experimental data when the same 38 cm burner is operated at half the power output (30 kW), yielding a shorter igniter flame. Once again the model is conservative, predicting somewhat greater upward fire growth than was seen experimentally. However, the model once again captures semi-quantitatively the essence of what occurred in the real tests – the flame spread about halfway up the corner and stopped. The predicted peak for the heat release rate was 52 kW; the experiments gave 42 and 71 kW.

Figure 5a also includes a model prediction of the estimated impact of the use of non-flame retarded vinyl ester resin in the same composite, subject to the same ignition source. Cone Calorimeter measurements on such composites show that they yield a heat release rate about 3 times higher than that from the brominated resin. The model predicts that this non-FR resin will yield rapid flame spread to the top of the corner. The increasing slope implies that the spread may keep on going up. Thus the value of the FR resin is clear though it should be noted, **as** seen in Figure 4, that it still allows some spread beyond the ignition source, which is undesirable since the threatened area of the structure is thereby enlarged.

Figure 5b compares model **and** experiment for the case of the 38 cm burner operated at 140 kW; note the shorter time scale. Here the time scale for growth is qualitatively correct but the quantitative comparison looks less good. There are at least two problems contributing to this. The model does not have spatially resolved incident heat flux data over the first 1.6 m of the height of the corner; it thus predicts a vertical line (instantaneous ignition over this height) where the data clearly indicate a spread of ignition times. The second problem is that the effect of the ceiling segment at the top of the corner in the experimental apparatus was more significant here. The strong igniter and the strong composite burning it produces yielded a flame which played extensively on the ceiling; the feedback from this ceiling section to the upward spreading flame **was** thus accentuated. This is a possible reason why the experimental data on upward spread did not show any slowing of the spread near the top of the corner **as** the model predicts. The strong flames are also thicker and thus able to radiate more toward the solid surfaces. This effect was approximated roughly in a second run of the model by adapting flame heat feedback data (flux vs height) for upward flame spread on tall slabs of poly(methyl methacrylate) by Orloff [9]. Here this provides a means to estimate the increased feedback from the thickening flames on the composite resin but it does not closely mimic the complex effects of a ceiling segment. Figure 5b shows that such effects have the expected qualitative effect of accelerating the flame spread near

the top of the corner.

The model predicts a *peak* heat release rate of 202 kW; the experiments gave an average peak of 268 kW. For the model case with the boosted heat feedback near the top of the corner, the peak heat release rate prediction was 244 kW; it would be higher if better data on the high flux region of the igniter were available. Given the tall igniter flame, the model predictions for this case would best have been tested against a configuration lacking a ceiling segment but such data are not available at present.

A model such as that described here contains a variety of approximations whose net effect is to render the model qualitative in nature. The model is best used to assess the expected trends of behavior as either fire exposure conditions or composite properties change. If the model has been calibrated against full-scale experimental data, as has been done to a limited extent here, it gains some credibility as a semi-quantitative tool for estimating expected fire response of the composite which it has been tested against. Given appropriate bench-scale input data on the behavior of other composite resins which do not introduce any different physical behavior in response to fire, the model might also be expected to be capable of at least correct trend predictions. Thus this model might be reasonably good for trend predictions with polyester and vinyl ester based composites which do not exhibit any significant geometry changes during fire exposure but only full-scale tests can confirm this.

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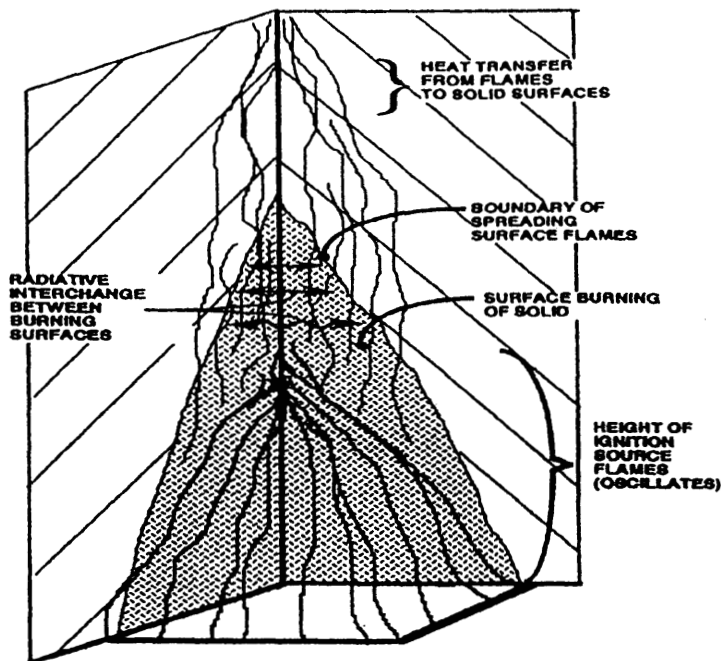


FIGURE 1. Elements of the corner fire growth process.

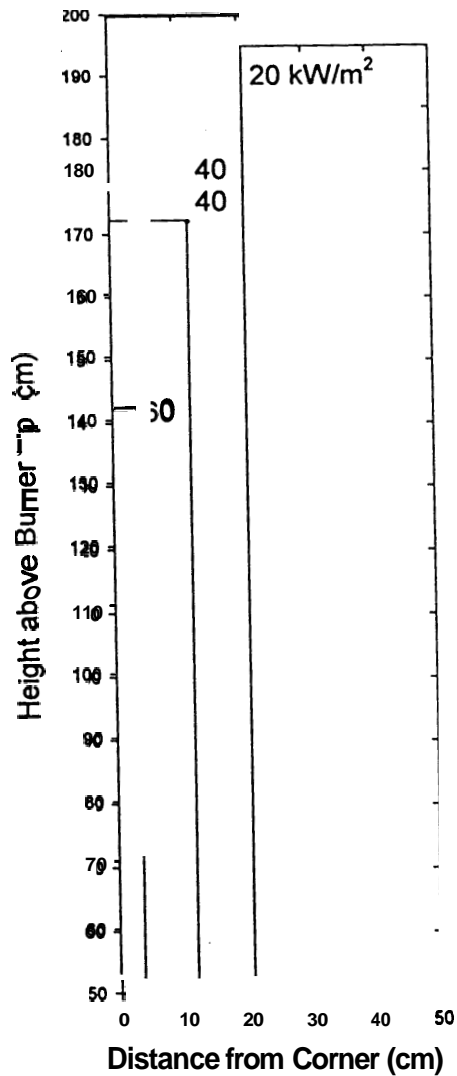
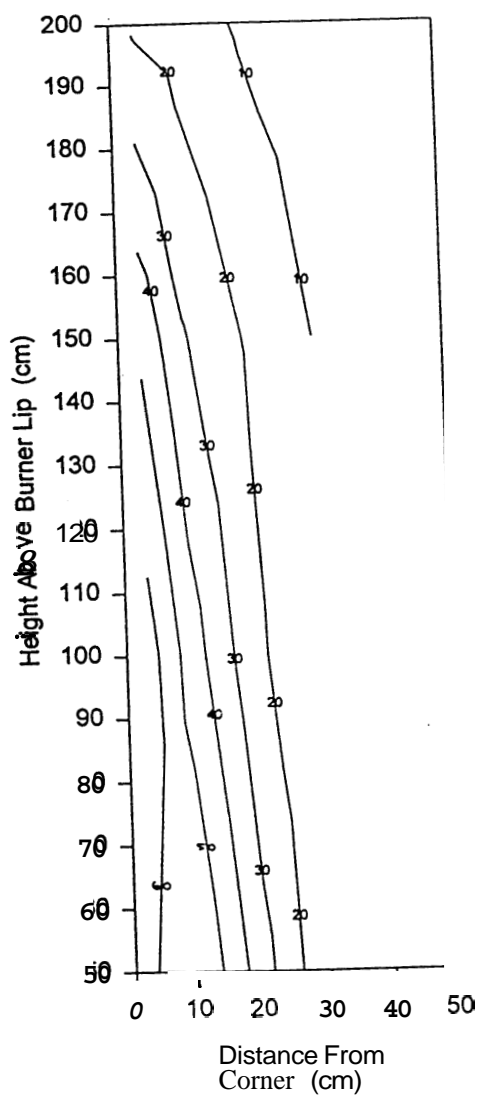


Figure 2 a) Isoflux lines based on measurements of total heat flux from 23 cm square burner operated at 60 kW

b) Nested rectangle approximation of this heat flux distribution

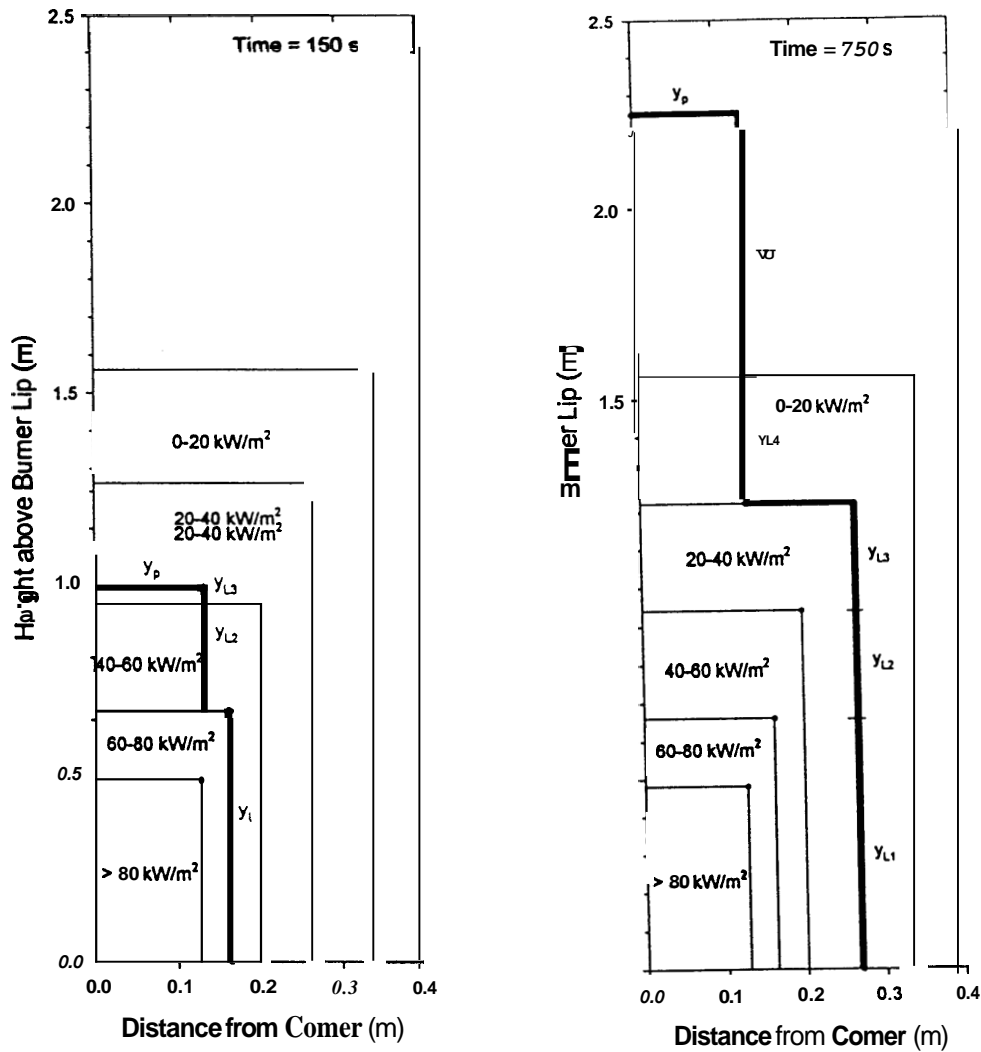


Figure 3 Model prediction of movement of upward and lateral pyrolysis fronts within the rectangularly-approximated total heat flux distribution from a 38 cm wide burner operated at 60 kW. Wider lines denote pyrolysis fronts at 150 and 750 seconds into igniter exposure.

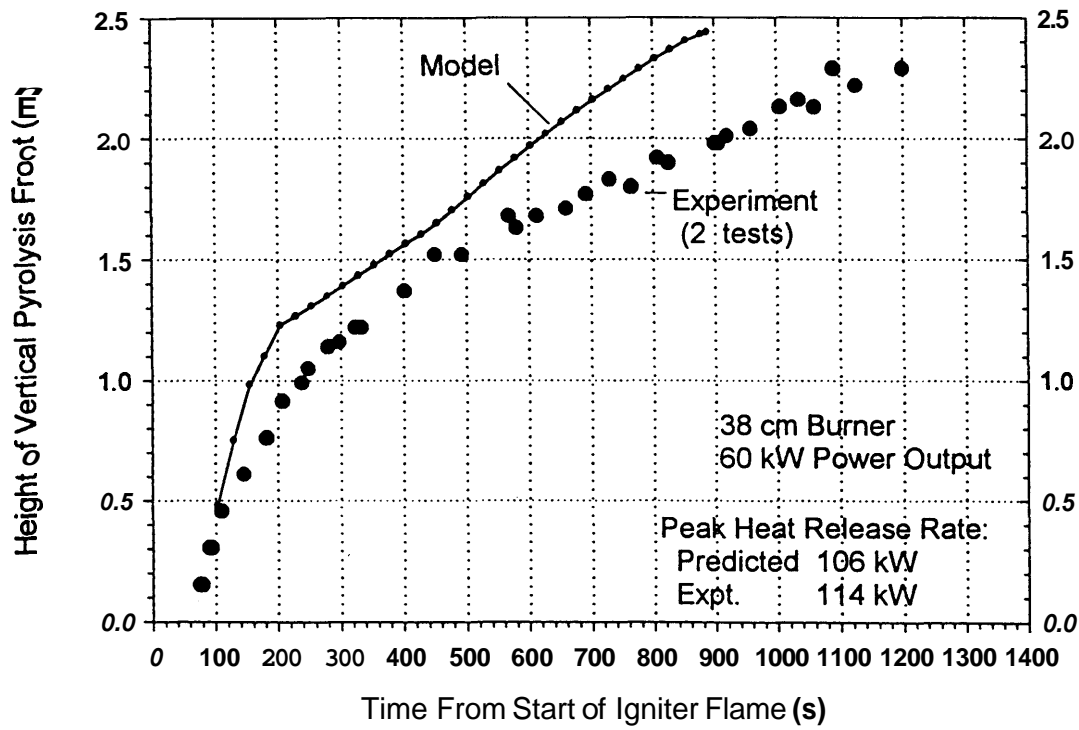


Figure 4 Comparison of model prediction and experiment for upward fire growth on FR vinyl ester/glass in corner configuration.

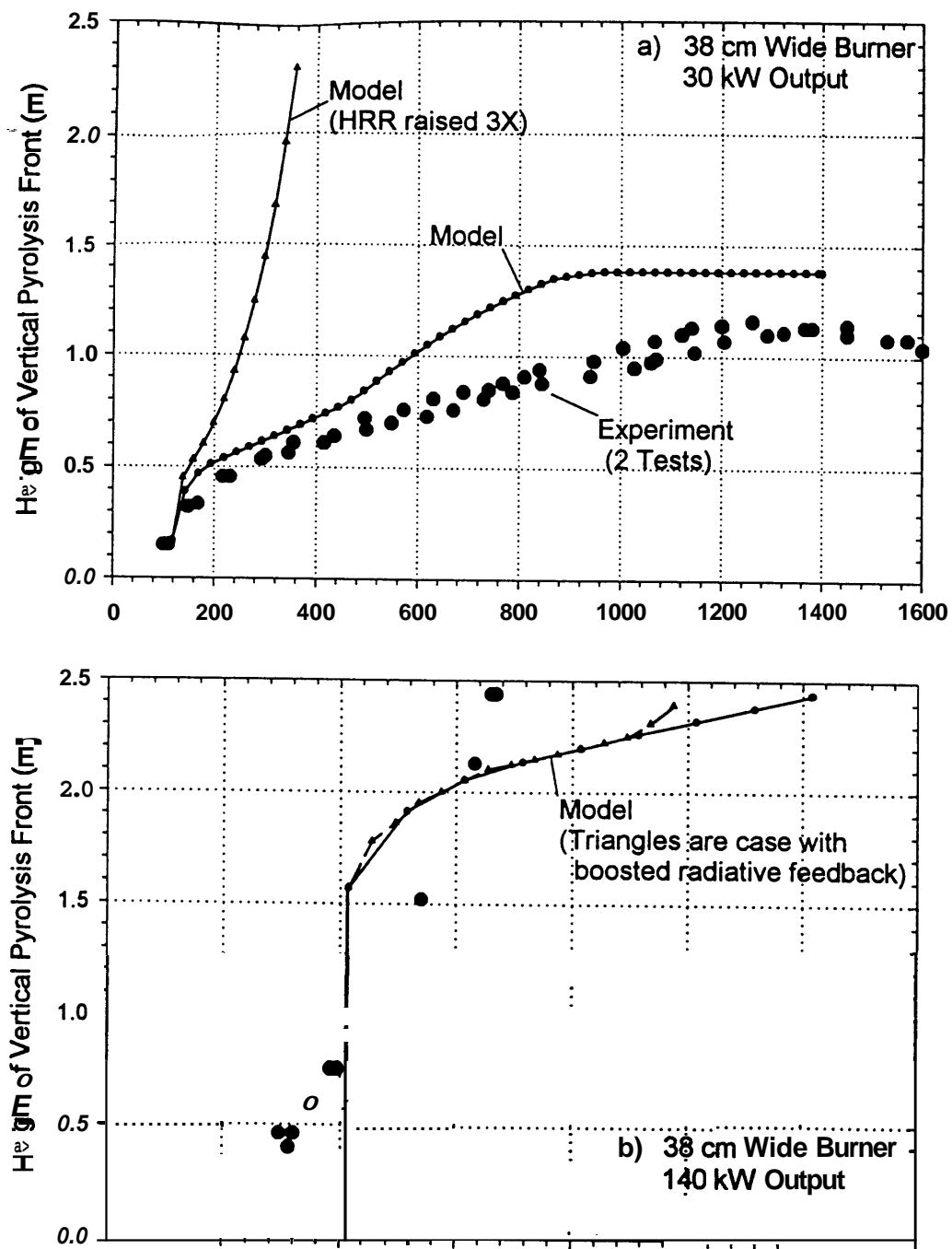


Figure 5 Comparisons of model predictions and experiment for upward fire growth.
a) 38 cm burner operated at 30 kW; b) 38 cm burner operated at 140 kW